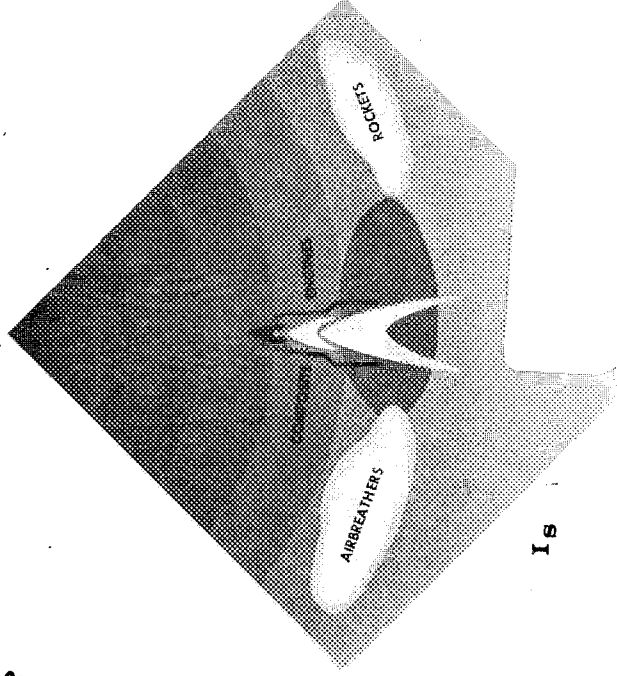


CLASSIFICATION CHANGE

DECLASSIFIED

By authority of *James A. Jenkins*
CIN. and by *James A. Jenkins* Date *3/11/75*
Declassified Document Control Section, NASA
Scientific and Technical Information Facility



Is

A STUDY OF COMPOSITE PROPULSION SYSTEMS FOR ADVANCED LAUNCH VEHICLE APPLICATIONS

SUMMARY REPORT (EXTENSION PHASE)

VOLUME 1

APRIL 1967

REPORT NO. 25,220

PREPARED UNDER NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION CONTRACT NAS7-377

THE MARQUARDT CORPORATION
LOCKHEED-CALIFORNIA COMPANY

DRF

A STUDY OF COMPOSITE PROPULSION SYSTEMS
FOR
ADVANCED LAUNCH VEHICLE APPLICATIONS
(EXTENSION PHASE)

VOLUME 1


SUMMARY REPORT

Report 25, 220

Contract: NAS7-377

Project: 5402

Prepared by:


B. J. Flornes
B. J. Flornes, Project Engineer




Approved by:

William J. D. Escher
W. J. D. Escher, Program Manager


R. E. Fisher
R. E. Fisher, Vice President
General Manager, ASTRO Division

The Marquardt Corporation
Van Nuys, California

April 1967


The following information is being furnished to you for your information only. It is not to be used in any way without the express written consent of The Marquardt Corporation.

See pages 173 and 174, the transmission of information is authorized.

DO NOT REPRODUCE OR TRANSMIT IN ANY MANNER WITHOUT THE EXPRESS WRITTEN CONSENT OF THE MARQUARDT CORPORATION.




DOWNWARD

12 PERIOD





LIST OF ILLUSTRATIONS

| <u>Figure</u> | | <u>Page</u> |
|---------------|--|-------------|
| 1 | Elemental Propulsion Systems | 2 |
| 2 | Composite Propulsion System | 3 |
| 3 | Main Program Structure and Documentation | 4 |
| 4 | Comparative Payload Performance Summary, Basic Program | 5 |
| 5 | Extension Phase Structure and Content | 8 |
| 6 | Supercharged Ejector Ramjet Engine, Class 3 | 10 |
| 7 | ScramLACE Engine, Class 3 | 12 |
| 8 | Baseline Launch Vehicle (ScramLACE Engine Shown) | 14 |
| 9 | System Payload Performance Summary | 15 |
| 10 | Summary of SERJ Fan Pressure Ratio Variation Payload Results | 16 |
| 11 | Summary of Recycle ScramLACE Payload Results | 17 |
| 12 | Summary of Recycle ScramLACE Payload Results | 18 |
| 13 | Reference Flight Paths, Flight Path Sensitivity Study | 19 |
| 14 | Summary of Flight Path Sensitivity Payload Results | 20 |

UNCLASSIFIED

TABLE OF CONTENTS

| | <u>Page</u> |
|---|-------------|
| FOREWORD | -i- |
| PREFACE | -ii- |
| SUMMARY | 1 |
| INTRODUCTION | 2 |
| A. Composite Propulsion Systems | 2 |
| B. Previous Effort Under Contract NAS7-377 | 3 |
| C. Extension Phase Effort | 7 |
| DISCUSSION OF RESULTS | |
| A. Supercharged Ejector Ramjet Engine Studies | 9 |
| B. ScramLACE Engine Studies | 11 |
| C. Vehicle/Mission Studies | 13 |
| Class 3/2' Comparison Results | 15 |
| SERJ Fan Pressure Ratio Variation Study Results | 16 |
| ScramLACE Exit Nozzle Study Results | 17 |
| Hydrogen Recycle ScramLACE Study Results | 18 |
| Flight Path Sensitivity Study Results | 19 |
| CONCLUSIONS | 21 |
| Performance and Design Studies | 21 |
| Special Subsystem Investigations | 21 |
| Vehicle Flight Path Variation Analysis | 22 |

UNCLASSIFIED

FOREWORD

This Volume I, Summary Report, presents in a highly abbreviated document the results given in the Main Technical Report, Volume 2. The study effort reported is an extension of an earlier basic program performed under the same National Aeronautics and Space Administration Contract NAS7-377.

The initial work was reported in Marquardt Report 25,194, dated September 1966. This document, in seven volumes, constitutes a fundamental reference for the present two-volume report.

PREFACE

The extension phase study under NAS7-377, "A Study of Composite Propulsion Systems for Advanced Launch Vehicle Applications," was performed for the Liquid Rocket Propulsion Technology Group of the Office of Advanced Research and Technology of the National Aeronautics and Space Administration. The Marquardt Corporation, supported by the Lockheed-California Company, accomplished the study described herein in the period June 1966-January 1967. Specific acknowledgements are given in Volume 2.

The Marquardt Corporation, on behalf of the study contractor team, extends its appreciation to the National Aeronautics and Space Administration for the opportunity to continue this evaluation of composite/rocket airbreathing propulsion systems, and to the NASA Project Manager and Technical Managers for their assistance in conducting the extension phase effort.

SUMMARY

A six-month extension phase effort under NASA Contract NAS7-377, previously published as Marquardt Report 25,194, has been performed by The Marquardt Corporation, assisted by the Lockheed-California Company.

The work, centering around two previously selected composite rocket/air-breathing launch vehicle engines, was to accomplish engineering verification and special engine subsystem investigations stemming from the previous study effort.

Conclusions which had been reached in the earlier program (Report 25,194) have been fundamentally upheld by the extension phase findings. Though engine performance and thrust/weight ratios were diminished by the increased technical penetration afforded by the extension, orbital payload performance decrease (5.6 and 11.7 percent for the two engines, respectively) was not considered critical. Avenues for improving performance and weight toward reversing these deficiencies have been identified.

In addition, engine cooling, operation, and structural make-up facets are now defined to the point that definite feasibility has been demonstrated at what is judged to be an acceptable level of confidence at this time. Supporting critical technology programs for composite engines previously identified, may now be meaningfully pursued in consonance with advanced launch vehicle planning being conducted at the national level.

INTRODUCTION

This report presents the results of an Extension Phase program under Contract NAS7-377 which comprises a broad, yet reasonably penetrating investigation of composite rocket/airbreathing propulsion systems as they might be applied to the problem of advanced launch vehicle propulsion. The basic program, performed in 1965-1966, by a team consisting of The Marquardt Corporation, Lockheed-California Company and the Rocketdyne Division of North American Aviation, Inc., has been reported in Marquardt Report 25,194, dated September 1966. The present report consisting of two volumes, a Summary Report (1) and the Main Technical Report (2), presents the result of a continuation of effort by The Marquardt Corporation, again supported by the Lockheed-California Company, performed in the period June 1966 through January 1967.

Following a brief introduction to the subject of Composite Propulsion Systems, the results achieved in the basic program (reported in Report 25,194) will be cursorily summarized. From this point of departure, the extension phase effort itself will be described somewhat in further detail by way of completing this introduction.

A. COMPOSITE PROPULSION SYSTEMS

Composite propulsion systems (as the term is used in this study) are single integrated powerplants made up of both rocket and airbreathing elements. The elemental propulsion systems which provide the basic building blocks for synthesizing composite engines are the familiar rocket and airbreathing systems, which are symbolically illustrated in Figure 1.



FIGURE 1. Elemental Propulsion Systems

If it is desired to incorporate the features of both elements (rocket and airbreather) in a single vehicle, two approaches are obvious. The elements may be installed either separately or integrally. The former may be termed a combination propulsion system. Thus, to illustrate the contrast, combination propulsion systems incorporate two or more elemental engine types in a nonintegrated installation, i.e. with little or no direct physical or process interaction between engine types within the vehicle's propulsion complement. However, combination systems were not studied in this effort.

If, however, the elements are physically integrated into a single propulsion system, having multi-modal operation capabilities, with cycle process interactions between elements, the result is a composite propulsion system, (Figure 2), the subject of the study.

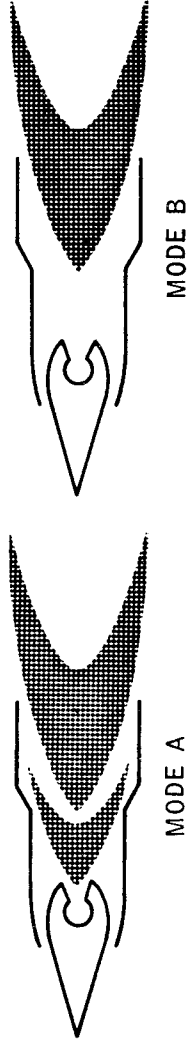


FIGURE 2. Composite Propulsion System

B. PREVIOUS EFFORT UNDER CONTRACT NAS7-377 (Marquardt Report 25,194)

In the basic study, Composite Propulsion System Powered Advanced Launch Vehicles were investigated to satisfy the following specific objectives:

1. To systematically appraise the significance of composite rocket/airbreathing engines to potential advanced launch vehicle missions in the period post 1975.
2. To determine the technology ramifications of composite engines with particular emphasis on delineating critical or pacing technology requirements.
3. To systematically and comprehensively document technical data which would be useful for further studies involving composite engines, with emphasis on vehicle/mission applications.

The first two objectives above formed the nucleus of the program's original problem statement. They stemmed directly from the attractive, at that time unconfirmed, potential of composite engines, which are intermediate in their characteristics with respect to pure rocket propulsion and conventional turbomachine centered airbreathing systems as suggested in the introductory description above. The third objective, in contrast, represented an intrinsic output of the study program, that is propulsion system information arranged for effective use by the aerospace technical community in subsequent studies involving composite propulsion.

The study was performed in conformance to a specific set of technical guidelines designed to be representative of the advanced launch vehicle area being addressed. The program structure and the basic methodology applied in the performance of the study is reflected in Figure 3. This figure indicates that the program was performed in three associated phases conducted serially after an initial preparatory effort. These progressive phases (labeled Classes 0, 1, and 2) investigated a decreasing number of a large group of composite concepts identified, generally the more attractive ones, with a successively deeper technical penetration into the engines and their vehicle/mission ramifications. A primary point of the figure is that the documentation developed during each of the three phases of the program provided useful engine information.

"A STUDY OF COMPOSITE PROPULSION SYSTEMS FOR ADVANCED LAUNCH VEHICLE APPLICATION"

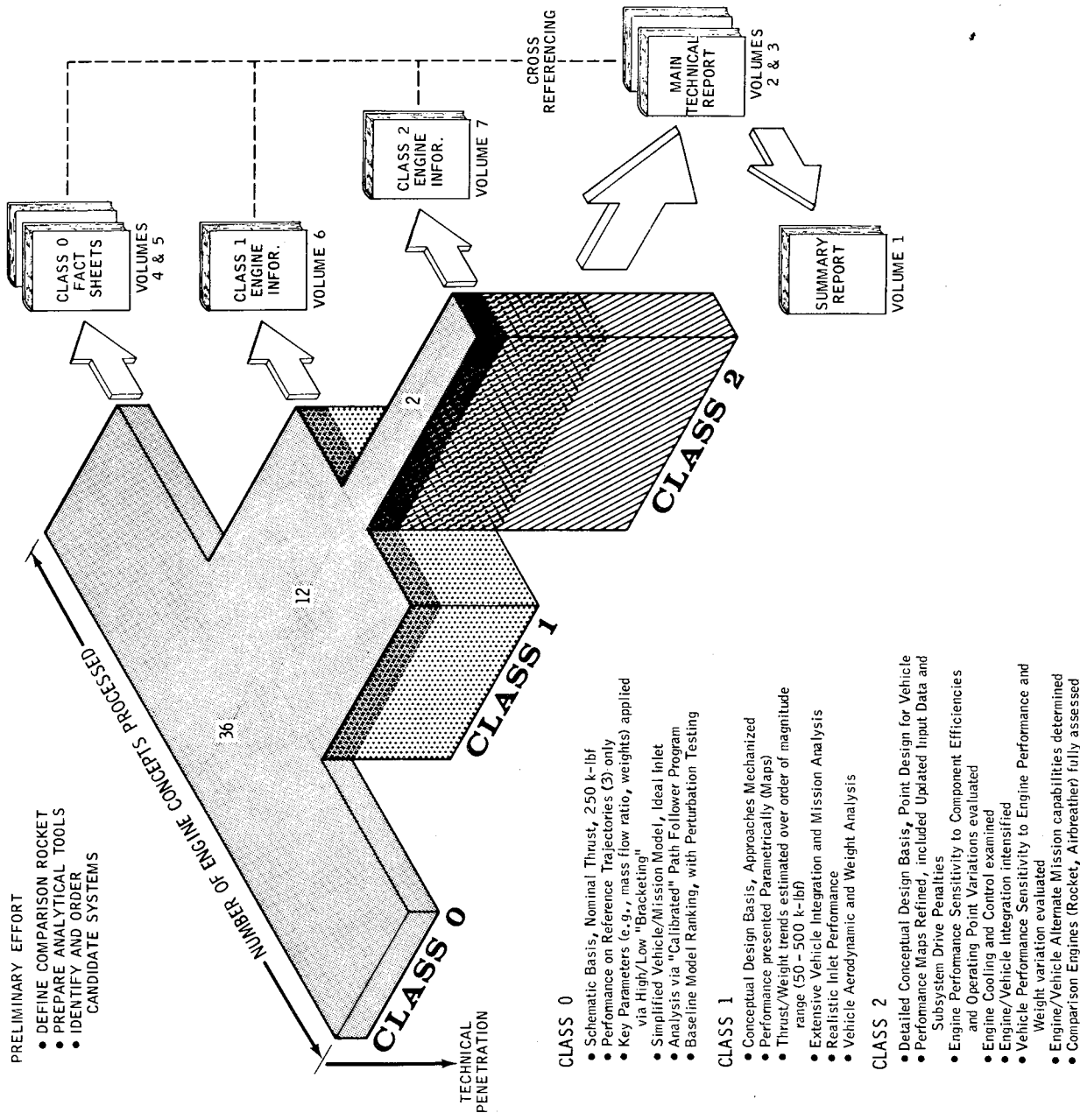


FIGURE 3. Main Program Structure and Documentation

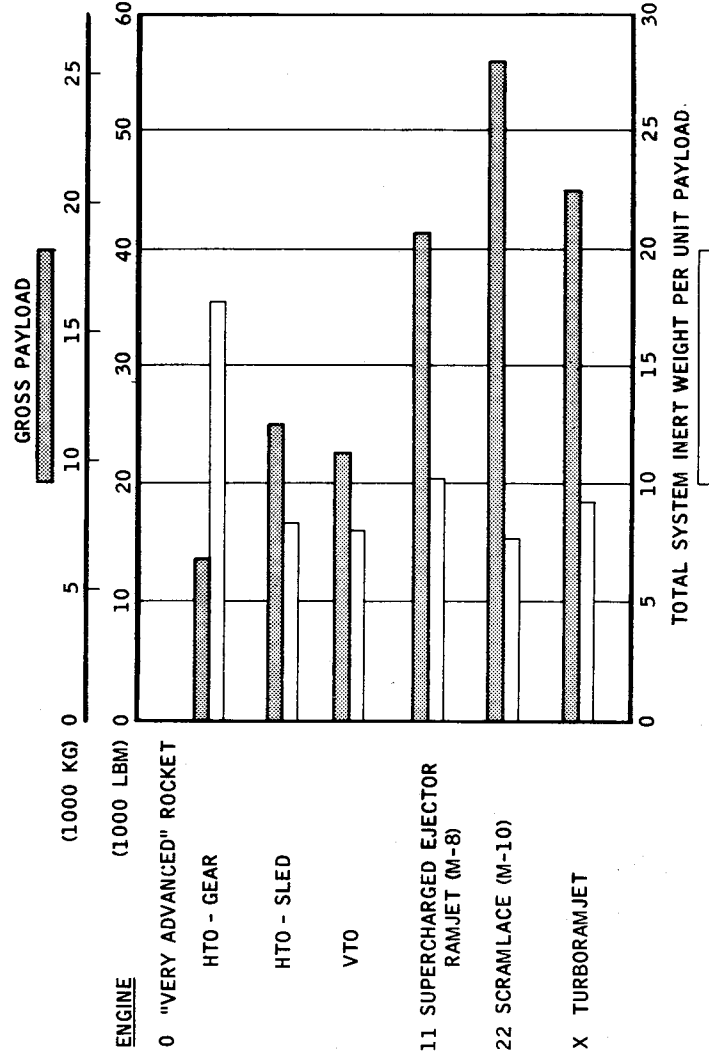
These engine information documents joined the final main technical report and a summary volume in comprising the basic program documentation issued prior to the present report.

Since, in its essence, the extension phase effort departs directly from the Class 2 phase effort (the right-hand portion of the Figure 3 representation), further comment will be made here regarding the results of this particular phase.

The Class 2 studies concentrated on two specific composite propulsion systems, the Supercharged Ejector Ramjet Engine (SERJ) and the ScramLACE Propulsion System. These systems, it will be recalled (Figure 3), resulted from the progressive screening of an original set of 36 composite candidate systems. Orbital payload performance and technology requirements associated with each concept, were the primary and secondary criteria for this selection.

The physical make-up of the Supercharged Ejector Ramjet and ScramLACE engines in their final configurations will be illustrated in subsequent figures. First, however, the relative payload performances of these two leading composite engines, as compared to advanced versions of all-rocket and conventional (turbomachine centered) all-airbreathing propulsion systems, shown below in Figure 4, is the key output of the initial study program.

Figure 4. Comparative Payload Performance Summary,
Basic Program



The darkened bars indicate, for the one million pound takeoff weight, two-stage vehicle, the gross payload delivered to the orbital condition for the assumed overall mission profile, from lift-off to landing. As a secondary figure of merit, the ratio of total system inert weight to payload delivered to orbit is also included as the open bar in Figure 4.

As can be noted, the Composite Propulsion system approach is indicated to provide a competitive situation with the comparison rocket and airbreathing system. In fact, substantiation of the thesis that Composite Propulsion systems can be a third, full contending approach -- along with the all-rocket and the turbomachine based airbreathing systems -- for the powerplant role in advanced launch vehicles was the principal finding of the basic study. Also, delineation of the technology requirements, particularly those for achieving a satisfactory predevelopment phase for acquiring the indicated Composite Propulsion system capability, was a signal output of the program.

Leading to the need for further study in what was to become the extension phase, as a direct output of the Class 2 study phase, a number of areas were identified as requiring additional analytical and design investigation:

1. The techniques employed for performance predictions did not fully provide for the fact that during some portions of the flight, complete thermodynamic and aerodynamic matching would not be accomplished. Also, internal process efficiencies, though believed estimated at realistic levels, required further evaluation.
2. The analysis suggested, but did not evaluate, the possibility that a fixed geometry exit nozzle might be feasible and attractive for the rectangular ScramLACE engine.
3. Weight studies and structural heating considerations were extracted largely from previous studies, whereas detailed heat transfer analysis would be ultimately required to confirm cooling feasibility. Structural analysis was pursued on a very simplified basis in which, for example, internal engine load paths were not actually quantified.
4. Inasmuch as the cycle performance capitalization on the heat sink characteristics of slush hydrogen (viz., recycle engines) was examined only in the initial phases of the study, further study appeared to be in order to identify the overall system performance/weight trade-off relationships.
5. Payload performance was calculated for a vehicle "maximum performance" ascent path characterized by relatively high dynamic pressure levels. The effect on payload of flying more lofted trajectories such as might be dictated by operational constraints, e.g. early abort, sonic overpressure, was not determined.
6. Finally, the fact that employment of the low pressure ratio (1.3) fan subsystem had proved quite satisfactory for the more attractive composite systems, enlargement of the range of pressure ratios (and bypass ratios) was indicated to define logical engine design points.

UNCLASSIFIED

The need for additional investigations as represented by the above listing resulted in the initiation of the extension phase program that is to be described in this report.

C. EXTENSION PHASE EFFORT (Reported Herein)

As noted above, the Extension Phase effort used as a point of departure, the Class 2 study phase of the main program. The effort did, in fact, concentrate on the two Class 2 propulsion systems noted in the previous section, SERJ and ScramLACE. To distinguish the results of the Extension Phase, these systems in their final versions were denoted Class 3 engines. The results summarized for the Extension Phase here are arranged in terms of the two engines, and the vehicle/mission results obtained with them. Responding directly to the work area needs listed at the end of the previous section as objectives, the task structure of the Extension Phase reflected six main tasks:

Task 1 (SERJ and ScramLACE), Engine performance investigation including subsystem design studies

Task 2 (SERJ and ScramLACE), Structures and cooling analyses and associated design studies

Task 3 (ScramLACE), Exit nozzle studies including both variable and fixed geometry approaches

Task 4 (ScramLACE), Recycle ScramLACE investigation including various recycle rates with tanked slush hydrogen

Task 5 (SERJ and ScramLACE), Flight path sensitivity study to investigate the payload ramifications of alternate flight path selection

Task 6 (SERJ), Fan pressure ratio investigation

The Extension Phase effort was performed by Marquardt, again supported by Lockheed, and utilized the identical terms of merit for the various studies as used in the basic program. These, it will be recalled, (Figure 4) are gross payload to orbit (primary) and total system inert weight per unit payload (secondary). The latter is viewed as a system hardware cost indicator. Lockheed performed the analyses of the payload ramifications of each of the above tasks, and performed the flight path sensitivity study (Task 5) as a sole effort. Marquardt performed the propulsion system analyses involved in the six task effort. Figure 5 graphically reflects the make-up and interrelationships of the program, reflecting clearly that the study centered about the two propulsion systems previously described.

UNCLASSIFIED

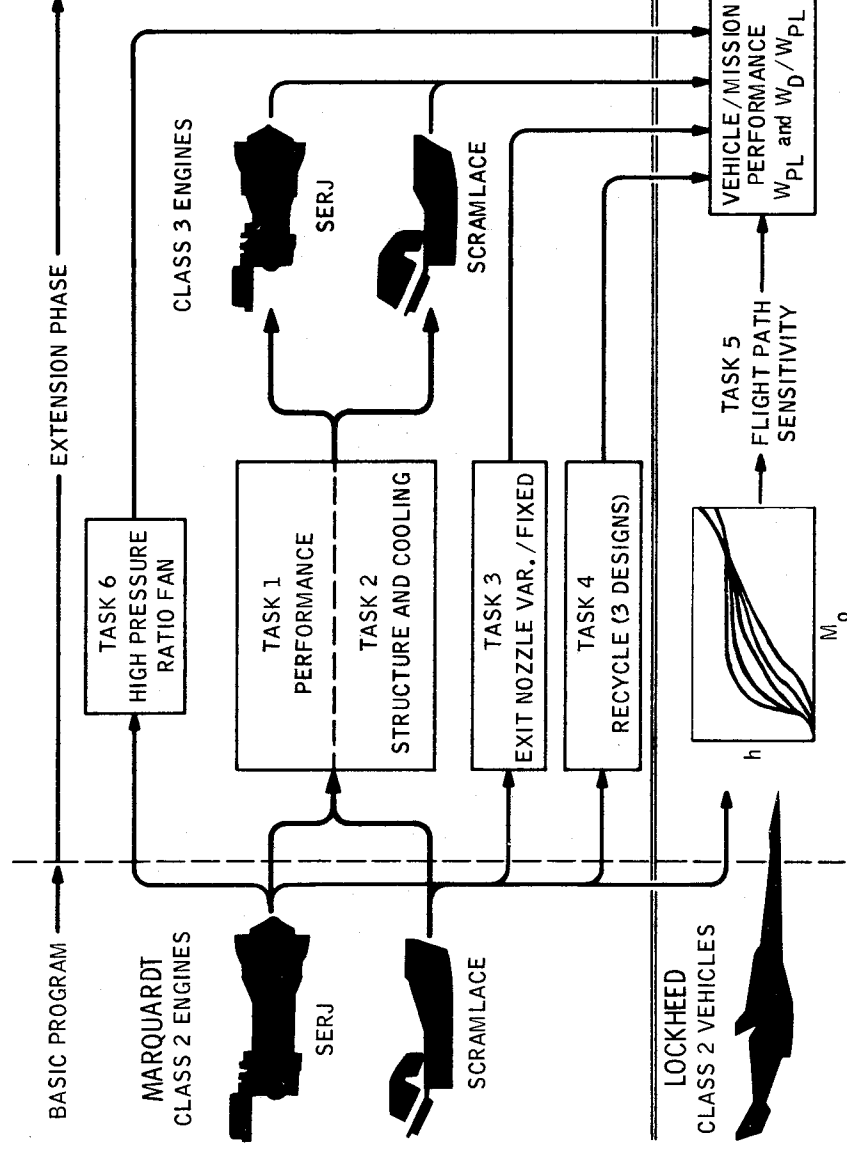


Figure 5. Extension Phase Structure and Content

The further development of the two basic program versions of the SERJ and Scramlance engine concepts (Class 2) which yielded the more definitive Class 3 configurations is reflected in Figure 5. This extension effort centered in Tasks 1 and 2, and also - for Scramlance - Task 3. These and the remaining Marquardt performed studies provided propulsion results for Lockheed's vehicle/mission performance analyses. The initial Lockheed work centered on the flight path sensitivity study (Task 5) for which basic program, i.e. Class 2, propulsion data was utilized.

As will be described, the Extension Phase effort significantly deepened the technical penetration into these representative composite propulsion systems and revealed the vehicle and mission payoff of these concepts to a significantly higher degree of confidence with respect to the previous effort. The results of the Extension Phase are briefly reviewed in the following section.

DISCUSSION OF RESULTS

A. Supercharged Ejector Ramjet Engine Studies

Performance studies on the Class 3 Supercharged Ejector Ramjet (SERJ) engine comprised three sequential facets: (1) component characteristic studies, (2) control approach definition, and (3) engine performance mapping. This task involved estimation of component performance and process efficiencies under off-design conditions with consideration of subsystem matching. A nominal engine control system approach for each operating mode was selected and described at a first-tier block diagram level.

Finally, from these findings, engine parametric performance maps were developed reflecting system thrust and specific impulse characteristics as a function of flight velocity and altitude for all applicable engine operating modes up to flight speeds of Mach 5.0. (Class 2 subsonic combustion ramjet mode performance for SERJ in the Mach 5.0 to 8.0 is still applicable to the Class 3 engine and can be obtained from Report 25,194.)

Structures and cooling studies were conducted with the dual objective of (1) confirming the feasibility of regeneratively cooling the SERJ engine at critical flight conditions, and (2) arriving at an engine weight estimate based on actual load and structural materials stress analyses.

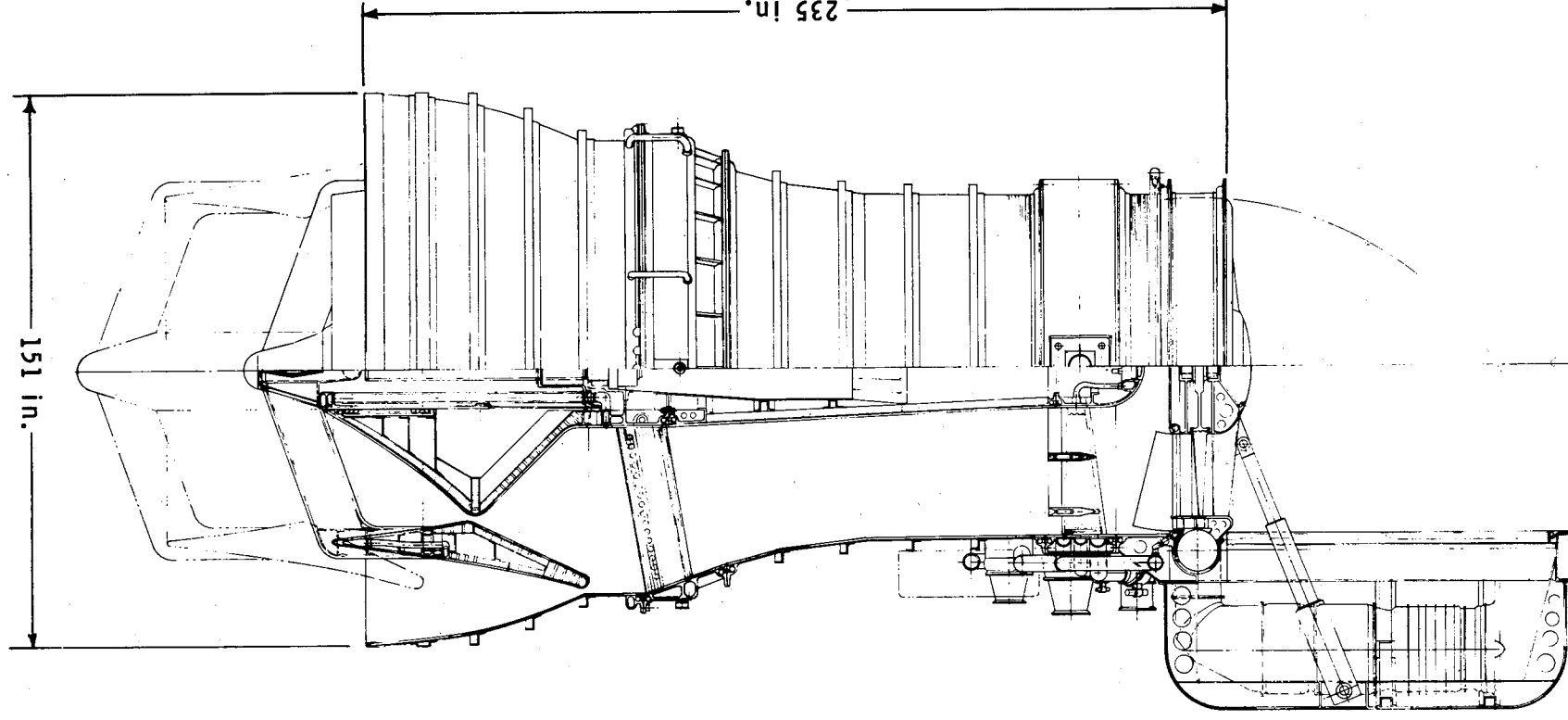
The heat transfer studies required the selection of a specific regenerative coolant flow circuit for the engine and that portion of the inlet aft of the cowl lip (radiation cooling was assumed for the forward section). Coolant temperatures, coolant passage heights, and metal hot-side wall temperatures were determined throughout the engine. Based on a 2500°R maximum acceptable hot wall temperature constraint, cooling adequacy for the SERJ engine was demonstrated for the identified critical Mach 8 subsonic combustion ramjet mode condition. Other operating modes and flight conditions also were checked as being satisfactory.

The revised configuration (Class 3) of the SERJ engine is shown in Figure 6. The basic performance and weight characteristics of this engine are listed below, with reference to the previous study (Class 2) estimates:

| | <u>Class 3</u> | <u>Class 2</u> | <u>Change</u> |
|-------------------------------------|----------------|----------------|---------------|
| Thrust, lbf (SLS*) | 203,000 | 215,000 | - 5.6% |
| Specific impulse, lbf/lbm/sec (SLS) | 452 | 494 | - 8.5% |
| Uninstalled weight, lbm | 12,900 | 11,940 | + 7.3% |
| Thrust/weight (SLS) | 15.8 | 18.0 | -12.2% |

*Sea level, static conditions

FIGURE 6. Supercharged Ejector Ramjet Engine, Class 3



A318-14

The payload ramifications of the somewhat diminished performance and weight values determined for the extension phase configuration of SERJ were of the order of 5-6 percent, relative to the earlier basic study results. This will be discussed further in the vehicle/mission study results to follow.

Figure 5 notes the high pressure ratio fan study (Task 6) conducted on the SERJ engine. In this task, based on a relatively simple methodology, a grouping of engine characteristics (weight, performance) for a range of fan subsystem pressure ratios of from 1.1 to 3.0 was established.

Based on the payload ramifications determined for this spectrum of fan subsystem capabilities, it is indicated that an increase in fan pressure ratio from the nominal Class 3 level of 1.3 to something slightly above 1.5 may be advisable for peaking out the engine payload performance potential. Going beyond 1.5 appears to offer rapidly diminishing - if not negative - returns. Depending on adequate runway length availability, subject to considerations of ascent flight path selection, beyond a pressure ratio of 1.5 to 1.8, the need for a primary rocket subsystem becomes questionable.

B. ScramLACE Engine Studies

Performance investigations of the ScramLACE engine for the initial ejector mode and intermediate speed subsonic combustion ramjet mode (SCRAMJET high speed mode was not further studied, see Report 25,194) included the same component estimation, control considerations and overall system performance aspects as already described for SERJ. In lieu of the fan subsystem, deepened analyses of the engine's air liquefaction heat exchanger subsystem were performed.

As a result of the favorable performance findings of the fixed exit nozzle task (to be described below), coupled with the relatively high weight penalties determined for the conventional variable nozzle investigated, the baseline ScramLACE engine (Class 3) was converted to a fixed exit configuration.

Structures and cooling studies were performed as described for SERJ. ScramLACE operating conditions of sea level static ejector mode, Mach 6 subsonic burning ramjet mode, and Mach 12 supersonic burning ramjet mode were examined in detail. Cooling feasibility was determined for the stated engine stoichiometric operating condition for all modes. A preferred hydrogen cooling circuit for the engine/inlet combination was defined which satisfied material operating temperature limits and available coolant bulk temperature rise, and provided for reasonable coolant pressure drops.

The extension phase version (Class 3) of the ScramLACE engine is represented in Figure 7. Overall performance and weight aspects of the engine are compared to the previous Class 2 version below:

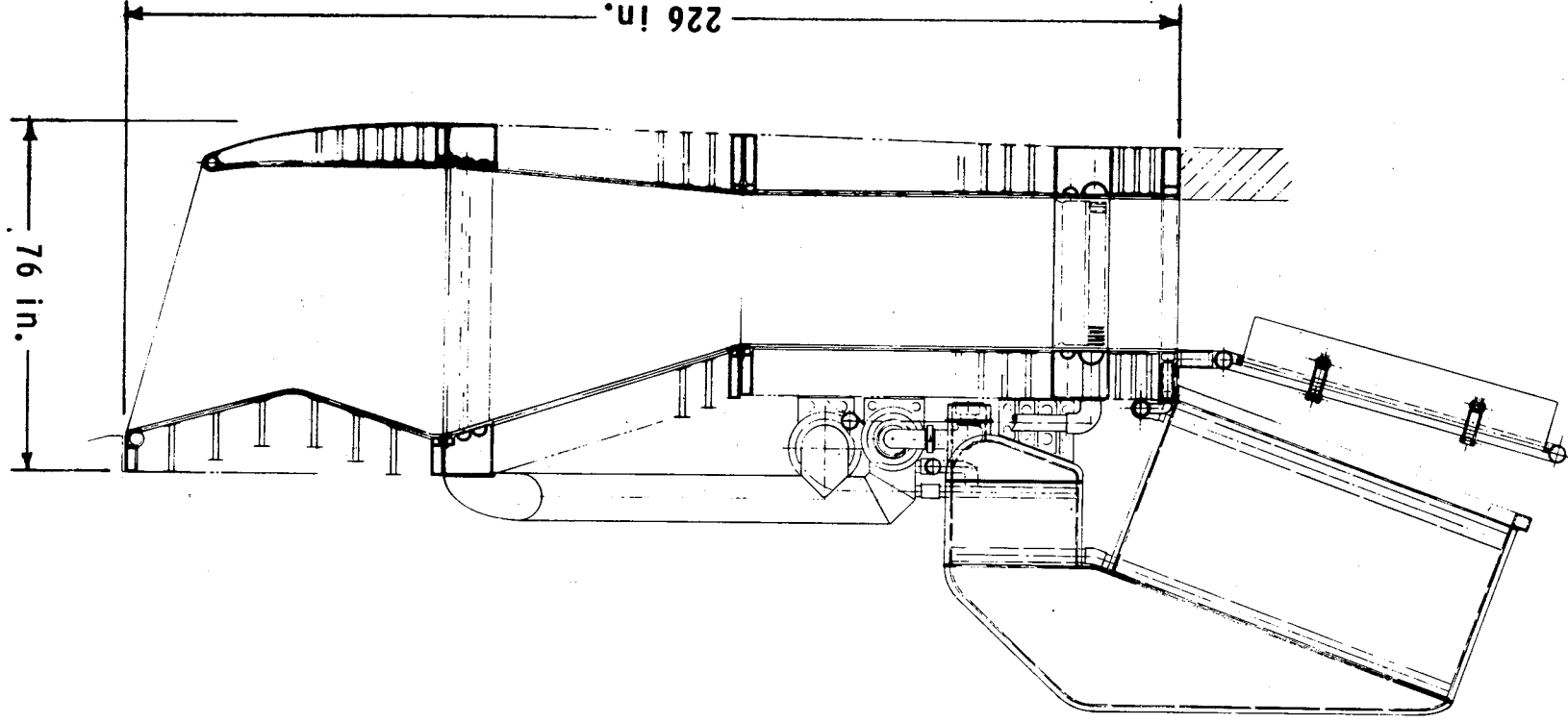


FIGURE 7. ScreamIACE Engine, Class 3

| | <u>Class 3</u> | <u>Class 2</u> | <u>Change</u> |
|-------------------------------------|----------------|----------------|---------------|
| Thrust, lbf (SLS) | 171,000 | 173,000 | - 1.2% |
| Specific Impulse, lbf/lbm/sec (SLS) | 1,240 | 1,344 | - 7.8% |
| Uninstalled weight, lbm | 12,450 | 10,452 | +16.0% |
| Thrust/Weight (SLS) | 13.7 | 16.5 | -16.9% |

As will be described in the vehicle/mission study discussion to be given, the significant performance/weight decrement reflected here represents a 11-12 percent orbital payload reduction for the ScramLACE system, with reference to the earlier Class 2 level results.

With reference to Figure 5 once more, the two additional study aspects of the extension phase which addressed the ScramLACE system are the exit nozzle studies (Task 3) and the hydrogen recycle engine analysis (Task 4).

The principal finding of the exit nozzle study, in addition to revealing the severe weight penalties associated with variable geometry two-dimensional hot structures of the conventional moving ramp type, was that a fixed exit design can yield a minimal loss in installed performance for the specified engine and flight conditions. Conversion of the baseline Class 3 system to the fixed exit design has already been described (Figure 7).

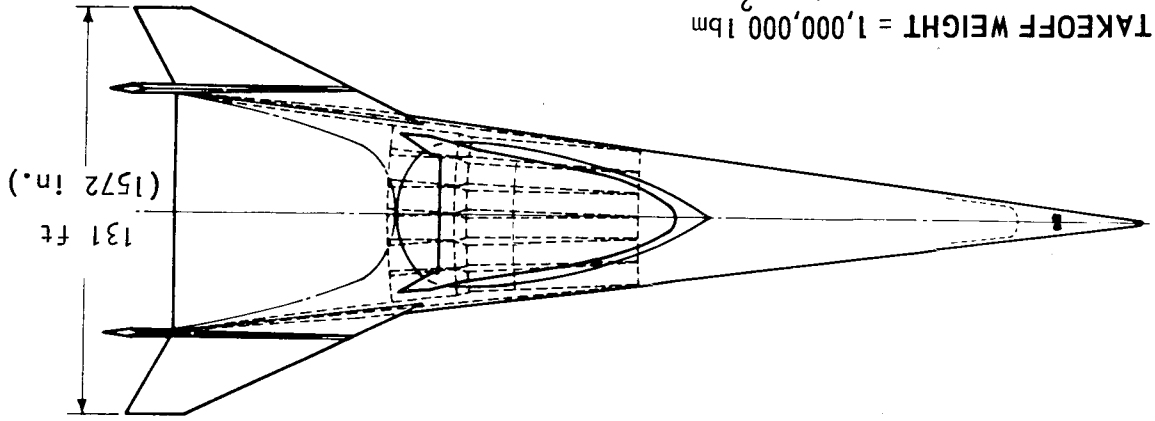
The further investigation of the possibilities of capitalizing significantly, in the air liquefaction cycle, on the performance attributes of subcooled slush hydrogen revealed a preferred design point in terms of a nominal hydrogen recycle rate. (An explanation of the hydrogen recycle technique and its physical ramifications will not be attempted here; Section V-D of Volume 2 should be consulted for this discussion.) The potential payload gains of the order of 10 percent via the recycle approach, are indicated in the next section.

C. Vehicle/Mission Studies

The mission payload results for each of the engine oriented tasks were determined by Lockheed. The results will be summarized graphically in bar chart format in this section. In addition to performing the payload assessment of Marquardt's engine oriented studies, it will be recalled (Figure 5) that Lockheed also conducted the flight path sensitivity study (Task 5).

The vehicle basis for the mission studies was that derived in the previous study phase (Class 2 effort) as described in Report 25,194, Volume 3. A representative baseline launch vehicle is depicted in Figure 8, as adopted from the previous report. The individual task vehicle/mission performance aspects are presented below on an individual basis.

Note that the previous results denoted Class 2' represents an adjusted or rationalized value for the prior published performance results. For details of this see Section VI-A-2 of Volume 2 of this report.



TAKEOFF WEIGHT = 1,000,000 lbm
 PLANFORM AREA = 16,224 ft²
 CAPTURE AREA MAX. = 408.5 ft²
 INITIAL THRUST/WEIGHT = 1.038

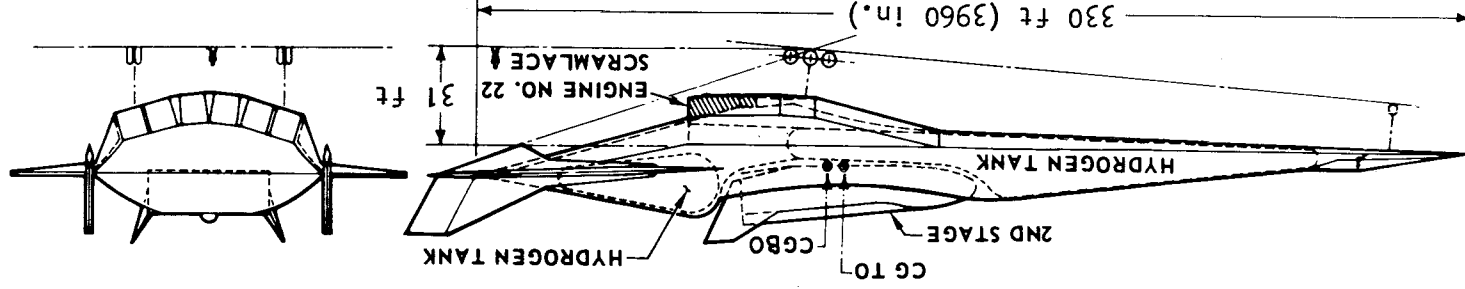
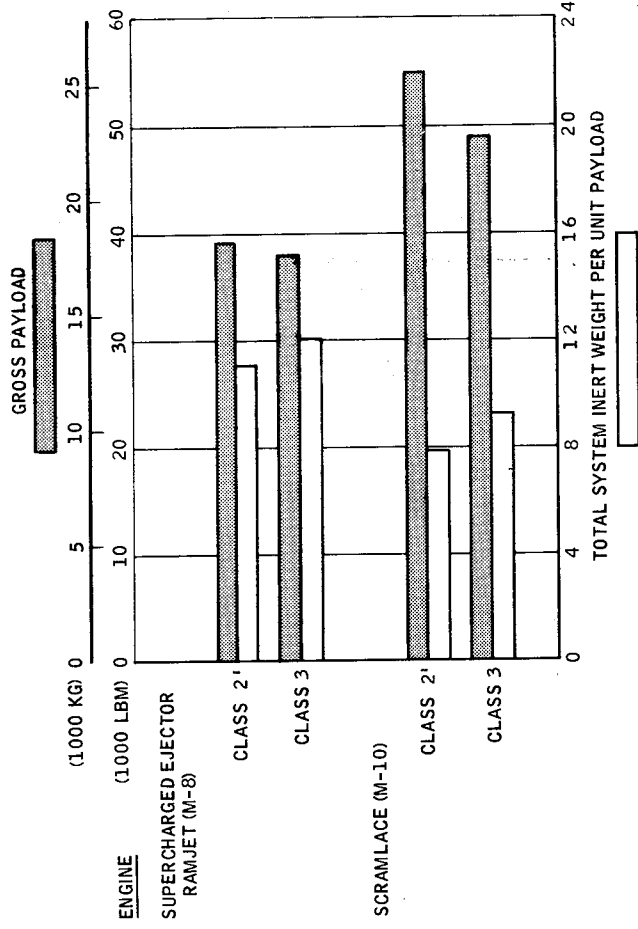


FIGURE 8. Baseline Launch Vehicle (Screwdrift Engine Shown)

Class 3/2' Comparison Results

Summary results of the significantly deepened performance, cooling and structures analyses on the revised SERJ and ScramLACE systems (i.e., Class 3 systems) are revealed in Figure 9:

Figure 9. SYSTEM PAYLOAD PERFORMANCE SUMMARY
CLASS 3/2' COMPARISON



A reduction in orbital payload was experienced for both engine systems as a result of increased engine weight and somewhat diminished performance. The payload values are listed below.

| | Class 3 | Class 2' | Change |
|--------------------------------|---------|----------|--------|
| SERJ system, payload, lbm | 37,000 | 39,200 | - 5.6% |
| ScramLACE system, payload, lbm | 49,000 | 55,500 | -11.7% |

SERJ Fan Pressure Ratio Variation Study Results

Figure 10. SUMMARY OF SERJ FAN PRESSURE RATIO VARIATION PAYLOAD RESULTS

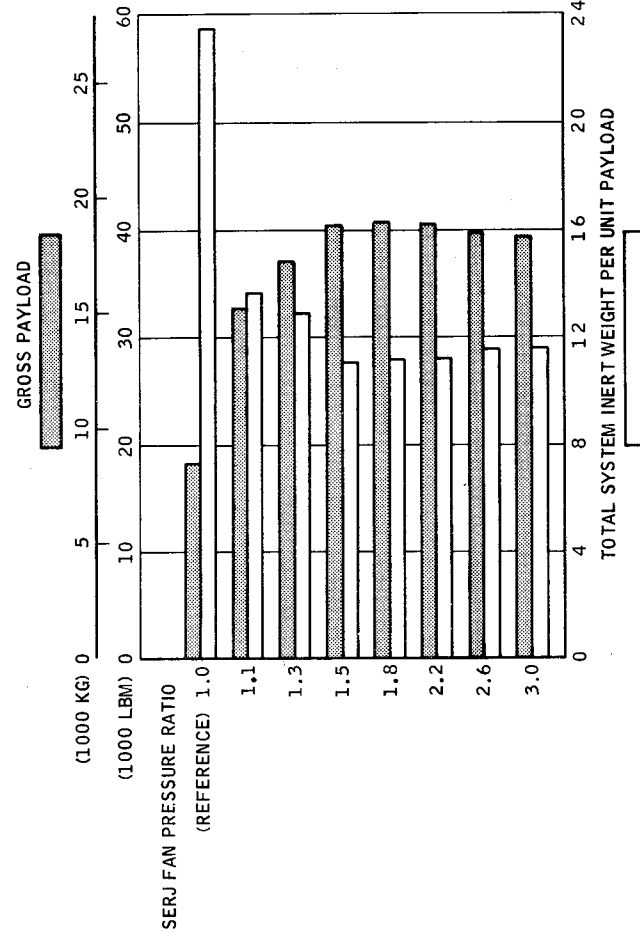
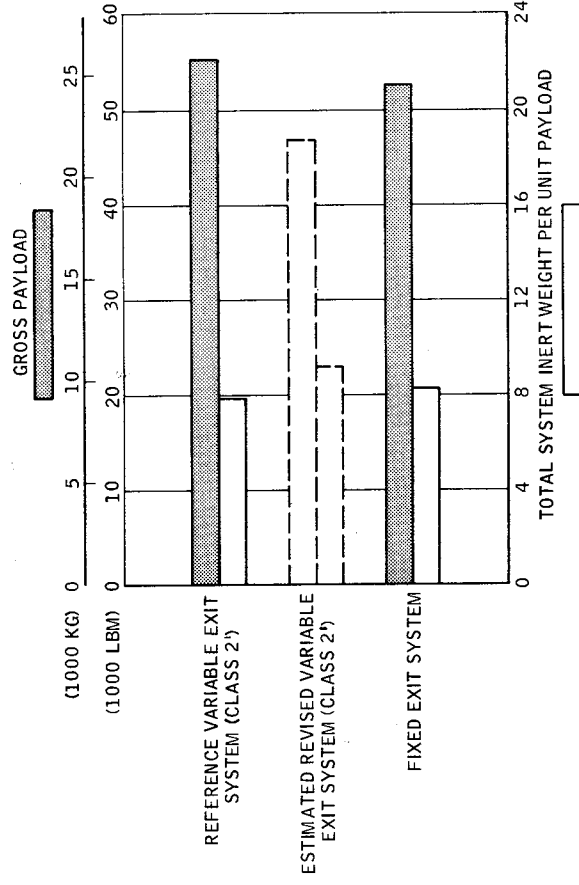


Figure 10 summarizes the SERJ fan pressure ratio variation results. Viewing the gross payload trends, the sharp increase from the reference ratio of 1.0 - essentially an Ejector Ramjet system with the weight penalty of a fan subsystem, but with no performance benefit - to the 1.1 pressure ratio system (78%), reflects the importance of the fan's contribution even with very low thrust addition implications. A peaking-out of further payload performance gains in the region of 1.5 - 1.8 pressure ratio is indicated. Beyond this number the rapidly increasing weight of the fan drive subsystem counterbalances the diminishing performance benefit of increasing pressure ratio. The hardware weight indicator shows the expected matching trend.

ScramLACE Exit Nozzle Study Results

Comparison of the payload performance ramifications of the fixed exit geometry for the ScramLACE engine, with respect to the previous variable exit design is made in Figure 11. A revised estimated variable exit engine, which is significantly heavier is also shown as the dashed bars.

Figure 11. SCRAMLACE EXIT NOZZLE STUDY PAYLOAD RESULTS



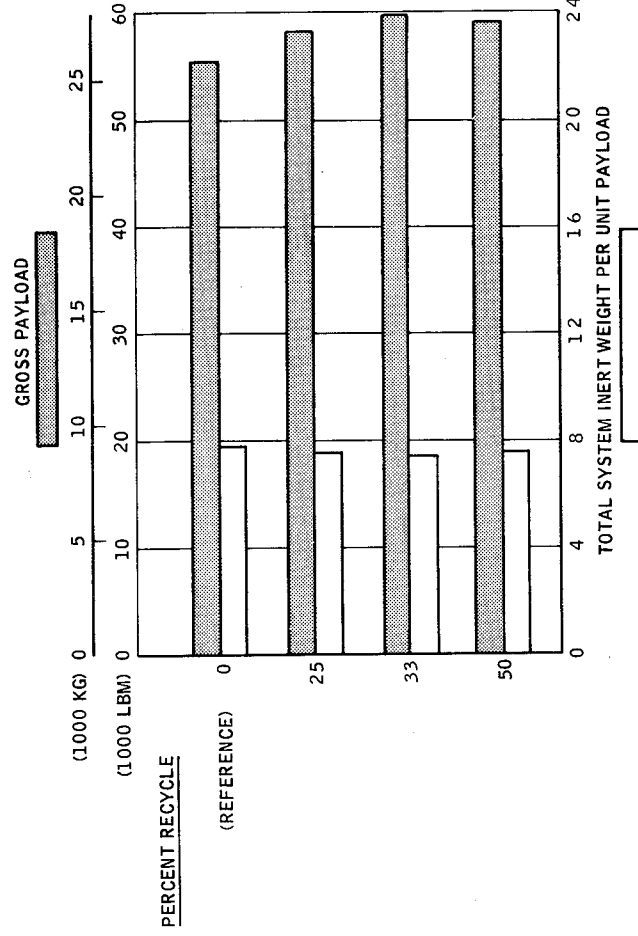
Investigation of the fixed exit version of ScramLACE revealed that, for acceleration operation along the reference high dynamic pressure flight path, performance is only modestly compromised, while engine weight is reduced, from the standpoint of a variable exit reference.

In view of the reevaluated variable exit design in the extension phase study, a very significant weight penalty is associated with the conventional moving-ramp variable nozzle design. However, exact ramification of this on engine thrust/weight was not determined. Nevertheless the dashed bars of Figure 11 are estimated payload performance values associated with this significantly heavier concept. Clearly, the fixed exit approach would seem, for the study conditions, to be a superior approach; hence the choice of a fixed exit for the Class 3 ScramLACE engine.

Hydrogen Recycle ScramLACE Study Results

Three hydrogen recycle versions of a baseline ScramLACE system are compared in terms of payload performance in Figure 12.

Figure 12. SUMMARY OF RECYCLE SCRAMLACE PAYLOAD RESULTS



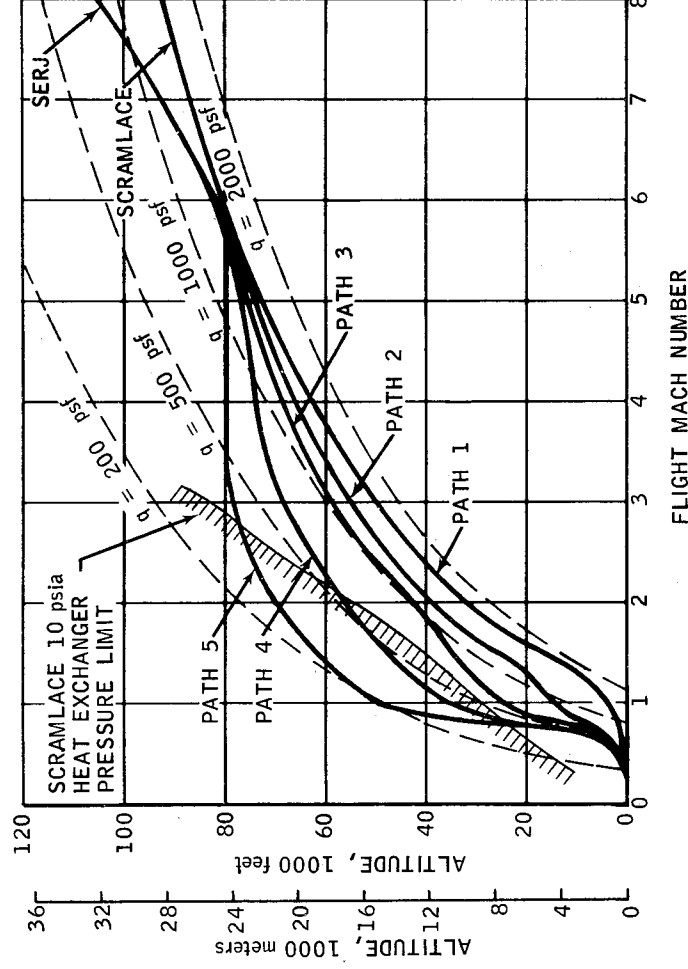
The recycle ScramLACE systems show an improvement in payload potential as anticipated with the recycle rate of 37 percent appearing to be about optimum. Figure 12 shows the trend of the recycle payload performance with reference to the basic ScramLACE with zero recycle and normal liquid hydrogen usage. The recycle rate of 33 percent showed the minimum (best) hardware weight indicator value of 7.45 for the three design points examined.

It is noted that although low speed specific impulse is very significantly increased (from 1344 to 2530 lbf/lbm/sec at sea level static conditions for a typical case) by recycle operation, there is an associated decrease in engine thrust/weight ratio (from 16.5 to 14.6 for the performance values cited above).

Flight Path Sensitivity Study Results

The objective of the flight path sensitivity task was, on a Class 2 basis, (pre-extension phase) to ascertain the payload performance significance of other than an optimal (for payload purposes) ascent path. On the figure below (Figure 13) this high performance path is noted "Path 1". The four alternative paths are shown as utilized in the task. It is noted that the ScramLACE system, because of indicated heat exchanger design limitations, was unable, without being redesigned, to ascend Paths 4 and 5.

Figure 13. Reference Flight Paths, Flight Path Sensitivity Study

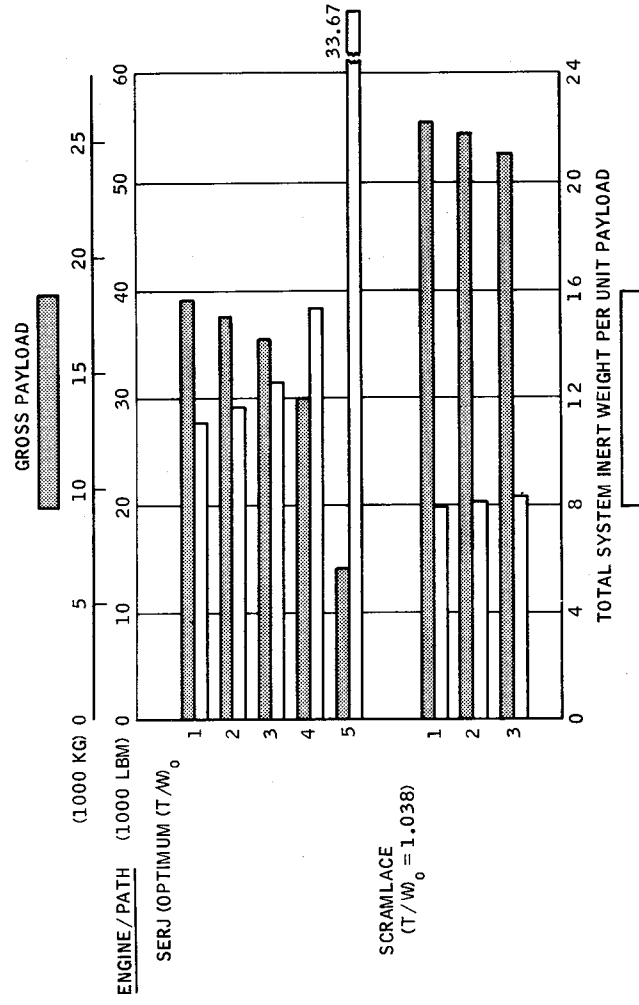


By way of explaining the choices of reference paths, the following rationale applies:

- Path 1 - For composite engines, typically a maximum payload path
- Path 2 - Nominally intermediate between Paths 1 and 3
- Path 3 - Typically a maximum payload path for turboramjet vehicles
- Path 4 - Representative of a sonic overpressure limited (2 psf) SST type ascent path
- Path 5 - Approximately half the dynamic pressure, at given flight Mach numbers, of Path 4

Figure 14 summarizes the payload performance achieved as the more highly lofted paths were followed. As indicated for SERJ the payload performance falls off very significantly only for the Path 4 and 5 operations. For the three lower paths investigated for the ScramIACE system, a somewhat lower sensitivity to flight path is noted.

Figure 14. SUMMARY OF FLIGHT PATH SENSITIVITY PAYLOAD RESULTS



CONCLUSIONS

The initial study effort under the contract, having considered broadly a large number of composite engines, singled out the Supercharged Ejector Ramjet (SERJ) and ScramLACE engines as worthwhile candidates for relatively near-term and far-term potential launch vehicle applications, respectively.

The extension phase comprised additional performance analysis and design penetration for these same engines. Specifically emphasized were (1) performance and design verification studies which examined subsystem matching, reevaluated earlier efficiency schedules, and considered engine cooling and structures; (2) special engine subsystem investigations, namely, fan pressure ratio variations (SERJ), and fixed and variable exit nozzle studies and air liquefaction mode performance improvement cycle options based on slush hydrogen (ScramLACE); and (3) engine payload performance as it is affected by vehicle ascent flight path variations. The principal findings of the extension phase investigation are as follows:

Performance and Design Studies

The performance results, which included the effects of the overall subsystem matching, and the modified engine weight estimates, derived from the structural analysis effort, resulted in a degradation of both specific impulse and uninstalled thrust/weight ratio for both powerplants. This in turn yielded modest payload weight reductions: 5.6 and 11.7 percent for SERJ and ScramLACE, respectively. For the one-million pound gross weight launch vehicle model, SERJ payload decreased from 39,200 lb to 37,000 lb, whereas ScramLACE payload decreased from 55,500 lb to 49,000 lb.

Satisfactory engine and inlet cooling can be effected at "worst" flight conditions. These were Mach 8 - 105,000 ft for SERJ, and Mach 12 - 130,000 ft (supersonic combustion mode) and Mach 6 - 85,000 ft (subsonic combustion mode) for ScramLACE. Regeneratively cooled engine duct materials locally approached 2500°R as a maximum. Available thermal barrier techniques such as ceramic coatings were not found necessary.

Special Subsystem Investigations

For SERJ, increasing fan pressure ratio from a nominal value of 1.3 to 1.5 or 1.8 can be expected to increase the delivered payload from 37,000 lb to about 40,500 lb, or a gain of the order of 10 percent. Further increases in pressure ratio, however, yield negligible gains. Above fan pressure ratios of 1.5 the primary rocket subsystem (supercharged ejector mode operation) is not required unless runway length limitations, higher and/or steeper flight paths, or other system requirements or mission constraints exist.

For the ScramLACE engine, using slush hydrogen technology to effect a recycle mode operation increased low speed specific impulse at the penalty of decreases in thrust/weight ratio. At an optimum recycle rate of 35 to 40 percent, a net payload improvement of about 4000 lb, above a reference of 55,500 lb, or about 8 percent can be achieved.

Again, for ScramLACE, detailed investigations of a conventional variable geometry exhaust nozzle revealed excessive engine weight penalties as compared to the earlier estimates. Based on positive indications from analyses of a fixed exit version, the baseline engine was converted to a fixed exit basis. Nevertheless, the engine remained somewhat heavier than the initial reference and performance over the flight range was also modestly compromised by the fixed exit. A payload advantage for the fixed exit version ($T/W = 18.3$) over an estimated revised variable exit engine ($T/W = 8.25$) is roughly estimated to be about 6000 lb; 52,900 lb compared to the estimated 47,000 lb payload of an updated variable exit ScramLACE system.

Vehicle Flight Path Variation Analysis

Payload performance of SERJ and ScramLACE in the launch vehicle model employed was found to be degraded if ascent flight paths are lofted substantially above the high dynamic pressure reference path. For example, on the higher flight path yielding maximum performance in a turboramjet powered vehicle, the following payload performance fall-off is observed for SERJ and ScramLACE: for SERJ payload decreased 3,700 lbs based on a reference of 39,200 lbs (9.5 percent), and for ScramLACE a decrement of 3000 lbs based on a reference of 55,500 lbs (5.4 percent).

DISTRIBUTION

| Copy No. | Transmitted to | Transmitted to |
|----------|--|--|
| 1. | NASA Office of Resident Representative Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, California 91103 Attn.: Office of Technical Information | NASA Langley Research Center Langley Station Hampton, Virginia 23365 Attn.: Dr. Floyd L. Thompson Director |
| 2. | NASA Office of Resident Representative Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, California 91103 Attn.: Contracts Management Division | NASA Lewis Research Center 21000 Brookpark Road Cleveland, Ohio 44135 Attn.: Dr. Abe Silverstein Director |
| 3. | NASA Office of Resident Representative Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, California 91103 Attn.: General Counsel for Patent Matters | NASA Marshall Space Flight Center Huntsville, Alabama 35812 Attn.: Hans G. Paul Code R-PAVED |
| 4 to 7. | NASA Headquarters Washington, D. C. 20546 Attn.: Chief, Liquid Propulsion Technology, RPL Office of Advanced Research and Technology | NASA Manned Spacecraft Center Houston, Texas 77001 Attn.: Dr. Robert R. Gilruth Director |
| 8 to 32. | NASA Scientific and Technical Information Facility P. O. Box 53 College Park, Maryland 20740 | NASA Office of Resident Representative Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, California 91103 Attn.: Robert W. Kamm Director |
| 33. | NASA Headquarters Washington, D. C. 20546 Attn.: Mr. Vincent L. Johnson Director, Launch Vehicles and Propulsion, SV Office of Space Science and Applications | NASA John F. Kennedy Space Center Cocoa Beach, Florida 32931 Attn.: Dr. Kurt H. Debus |
| 34. | NASA Headquarters Washington, D. C. 20546 Attn.: Mr. Edward L. Gray Director, Advanced Manned Missions, MT Office of Manned Space Flight | Aeronautical Systems Division Air Force Systems Command Wright-Patterson Air Force Base Dayton, Ohio 45433 Attn.: D. L. Schmidt Code ASCMCO-2 |
| 35. | NASA Ames Research Center Moffett Field, California 94035 Attn.: Mr. Clarence A. Syvertson Mission Analysis Division | Air Force Missile Development Center Holloman Air Force Base, New Mexico Attn.: Maj. R. E. Bracken Code MORT |
| 36. | Marshall Space Flight Center Huntsville, Alabama 35812 Attn.: Technical Monitor Mr. Donald Thompson | Air Force Missile Test Center Patrick Air Force Base, Florida Attn.: L. J. Ullian |
| 37. | Langley Research Center Langley Station Hampton, Virginia 23365 Attn.: Mr. Kenneth Pierpont | Air Force Systems Division Air Force Unit Post Office Los Angeles 45, California Attn.: Col. Clark Technical Data Center |
| 38. | NASA Ames Research Center Moffett Field, California 94035 Attn.: Mr. Thomas Gregory Mission Analysis Division | Arnold Engineering Development Center Arnold Air Force Station Tullahoma, Tennessee Attn.: Dr. H. K. Doetsch |
| 39, 40. | NASA Ames Research Center Moffett Field, California 94035 Attn.: Harvey J. Allen Director | Bureau of Naval Weapons Department of the Navy Washington 25, D. C. Attn.: J. Kay RTMS-41 |
| 41, 42. | NASA Goddard Space Flight Center Greenbelt, Maryland 20771 Attn.: Merland L. Mosson Code 620 | Defense Documentation Center Headquarters Cameron Station, Building 5 5010 Duke Street Alexandria, Virginia 22314 Attn.: TISA |
| 43, 44. | NASA Jet Propulsion Laboratory California Institute of Technology 4800 Oak Grove Drive Pasadena, California 91103 Attn.: Henry Burlage, Jr. Propulsion Div., 38 | Headquarters, U. S. Air Force Washington 25, D. C. Attn.: Col. G. K. Stambaugh AFRST |

DISTRIBUTION (Continued)

| Copy No. | Transmitted to | Copy No. | Transmitted to |
|----------|---|----------|---|
| 65. | Picatinny Arsenal Dover, New Jersey 07801 Attn.: I. Forsten, Chief Liquid Propulsion Laboratory SMTPA-DL | 78. | Astropower Laboratory Douglas Aircraft Company 2121 Paularino Newport Beach, California 92663 Attn.: Dr. George Moe Director, Research |
| 66. | Air Force Rocket Propulsion Laboratory Research and Technology Division Air Force Systems Command Edwards, California 93523 Attn.: H. Main, RPRR | 79. | Astrosystems International, Inc. 1275 Bloomfield Avenue Fairfield, New Jersey 07007 Attn.: A. Mendenhall |
| 67. | Research and Technology Division Air Force Aero Propulsion Laboratory Wright-Patterson Air Force Base, Ohio 45433 Attn.: H. C. Long, APRP | 80. | Atlantic Research Corporation Edsall Road and Shirley Highway Alexandria, Virginia 22314 Attn.: A. Scurlock |
| 68. | U. S. Atomic Energy Commission Technical Information Services Box 62 Oak Ridge, Tennessee Attn.: A. P. Ruber Oak Ridge Gaseous Diffusion Plant (ORGDGP) P. O. Box P | 81. | Beech Aircraft Corporation Boulder Division Box 651 Boulder, Colorado Attn.: J. H. Rodgers |
| 69. | U. S. Army Missile Command Redstone Arsenal Alabama 35809 Attn.: Dr. Walter Wharton | 82. | Bell Aerosystems Company P. O. Box 1 Buffalo, New York 14240 Attn.: W. M. Smith |
| 70. | U. S. Naval Ordnance Test Station China Lake, California 93557 Attn.: Chief, Missile Propulsion Division Code 4562 | 83. | Bendix Systems Division Bendix Corporation 3300 Plymouth Road Ann Arbor, Michigan Attn.: John M. Brueger |
| 71. | Air Force Systems Command Space Systems Division Inglewood, California 90045 Attn.: Lt. Col. Kenneth Mc Aeron | 84. | Boeing Company P. O. Box 3707 Seattle, Washington 98124 Attn.: J. D. Alexander |
| 72. | Chemical Propulsion Information Agency Applied Physics Laboratory 8621 Georgia Avenue Silver Spring, Maryland 20910 Attn.: Neil Safer | 85. | Missile Division Chrysler Corporation P. O. Box 2628 Detroit, Michigan 48231 Attn.: John Gates |
| 73. | Aerojet-General Corporation P. O. Box 296 Azusa, California 91703 Attn.: L. F. Kohrs | 86. | Wright Aeronautical Division Curtiss-Wright Corporation Wood-Ridge, New Jersey 07075 Attn.: G. Kelley |
| 74. | Aerojet-General Corporation P. O. Box 1947 Sacramento, California 95809 Attn.: R. Stiff Technical Library, Bldg. 2015, Dept. 2410 | 87. | Missile and Space Systems Division Douglas Aircraft Company, Inc. 3000 Ocean Park Boulevard Santa Monica, California 90406 Attn.: R. W. Hallett Chief Engineer, Advanced Space Tech. |
| 75. | Aeromotronic Philco Corporation Ford Road Newport Beach, California 92663 Attn.: D. A. Carrison | 88. | Aircraft Missiles Division Fairchild Hiller Corporation Hagerstown, Maryland 10 Attn.: J. S. Kerr |
| 76. | Aerospace Corporation 2400 East El Segundo Boulevard P. O. Box 95085 Los Angeles, California 90045 Attn.: John G. Wilder Propulsion Dept. MS-2293 | 89. | General Dynamics/Astronautics P. O. Box 1128 San Diego, California 92112 Attn.: Frank Dore Library & Information Services (128-00) |
| 77. | Arthur D. Little, Inc. 20 Acorn Park Cambridge, Massachusetts 02140 Attn.: E. Karl Bastress | 90. | Re-Entry Systems Department General Electric Company 3198 Chestnut Street Philadelphia, Pennsylvania 19101 Attn.: F. E. Schultz |

UNCLASSIFIED

DISTRIBUTION (Continued)

| COPY NO. | Transmitted to | COPY NO. | Transmitted to |
|----------|---|----------|---|
| 91. | Advanced Engine & Technology Dept. General Electric Company Cincinnati, Ohio 45215 Attn.: D. Suichu | 105. | Republic Aviation Corporation Farmingdale Long Island, New York Attn.: Dr. William O'Donnell |
| 92. | Grumman Aircraft Engineering Corp. Bethpage, Long Island New York Attn.: Joseph Gavin | 106. | Space-General Corporation 9200 East Flair Avenue El Monte, California 91734 Attn.: C. E. Roth |
| 93. | Ling-Temco-Vought Corporation Astronautics P. O. Box 5907 Dallas, Texas 75222 Attn.: Warren C. Trent | 107. | Stanford Research Institute 325 Ravenswood Avenue Menlo Park, California 94025 Attn.: Lionel Dickinson |
| 94. | Lockheed-California Company 2555 North Hollywood Way Burbank, California 91503 Attn.: G. D. Brewer | 108. | Space Technology Laboratories TRW Incorporated One Space Park Redondo Beach, California 90278 Attn.: G. W. Elverum |
| 95. | Lockheed Missiles and Space Company P. O. Box 504 Sunnyvale, California 94088 Attn.: Y. C. Lee | 109. | TAPCO Division TRW, Incorporated 23555 Euclid Avenue Cleveland, Ohio 44117 Attn.: P. T. Angell |
| 96. | Lockheed Propulsion Company P. O. Box 111 Redlands, California 92374 Attn.: H. L. Thackwell | 110. | Thiokol Chemical Corporation Huntsville Division Huntsville, Alabama Attn.: John Goodloe |
| 97. | Baltimore Division Martin-Marietta Corporation Baltimore, Maryland 21203 Attn.: John Calathes (3214) | 111. | Research Laboratories United Aircraft Corporation 400 Main Street East Hartford, Connecticut 06108 Attn.: Erle Martin |
| 98. | Denver Division Martin-Marietta Corporation P. O. Box 179 Denver, Colorado 80201 Attn.: J. D. Goodlette (A-241) | 112. | United Aircraft Corporation Pratt and Whitney Aircraft Division East Hartford, Connecticut 06108 Attn.: W. Sens |
| 99. | McDonnell Aircraft Corporation P. O. Box 516 Municipal Airport St. Louis, Missouri 63166 Attn.: R. A. Herzmark | 113. | United Aircraft Corporation Pratt and Whitney Aircraft Division Florida Research and Development Division West Palm Beach, Florida 33401 Attn.: R. Coar |
| 100. | Space & Information Systems Division North American Aviation, Inc. 12214 Lakeview Boulevard Downey, California 90241 Attn.: H. Storms | | |
| 101. | Rocketdyne North American Aviation, Inc. 6633 Canoga Avenue Canoga Park, California 91304 Attn.: E. B. Monteath Library, 586-306 | | |
| 102. | Northrop Space Laboratories 3401 West Broadway Hawthorne, California Attn.: Dr. William Howard | | |
| 103. | Astro-Electronics Division Radio Corporation of America Princeton, New Jersey 08540 Attn.: S. Fairweather | | |
| 104. | Reaction Motors Division Thiokol Chemical Corporation Denver, New Jersey 07822 Attn.: Arthur Sherman | | |

UNCLASSIFIED